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Mechanical properties of articular cartilage covered by the meniscus

A. Thambyah Ph.D.*, A. Nather M.D. and J. Goh Ph.D.
Department of Orthopaedic Surgery, National University of Singapore, Lower Kent Ridge Road, Singapore 119074, Republic of Singapore

Summary

Objective: To investigate the mechanical properties and morphological characteristics of articular cartilage on the tibial plateau of human knees, including the region covered by the meniscus.

Design: Using a 1-mm diameter flat-ended cylindrical probe to apply a constant load (0.6 MPa) at specific sites on the tibial plateau, the mechanical properties of articular cartilage were studied using seven cadaver knees. Comparison was made between data obtained by the cartilage covered by the meniscus and that not covered. This was done for both the medial and lateral plateaus. Histological sections of the articular cartilage were also performed to study differences between cartilage from these regions of the tibial plateau.

Results: Compared to cartilage that was not covered by the meniscus, the articular cartilage beneath the meniscus showed a significantly ($P < 0.05$) larger modulus by as much as 70%, and was less thick by about 40%. Also, the subchondral bone quantity and calcified layer thickness were observed to be significantly lesser in the regions covered by the meniscus.

Conclusions: Our findings revealed a significant difference between the mechanical properties and associated structures of articular cartilage in the region covered by the meniscus compared with the articular cartilage not covered by the meniscus.

Key words: Biomechanics, Tibial plateau, Articular cartilage, Topographical variation.

Introduction

The meniscus and cruciate ligaments play important roles in weight-bearing and stability of the knee joint[1–3]. In a cruciate ligament and meniscus deficient knee joint, the kinematics is altered with a subsequent weight-bearing tibiofemoral engagement of articular cartilage beneath the meniscus being a highly-likely, yet abnormal situation[4–9]. Prospective studies using magnetic resonance imaging of patients showed that the presence of meniscal and anterior cruciate ligament tears was associated with more rapid cartilage loss[10].

The importance of the meniscus in protecting the articular cartilage has been shown in animal studies[11,12] where groups treated with a sham operation had no cartilage damage, while groups with meniscectomy resulted in significant macroscopic and microscopic damage to the articular cartilage in the medial compartment[12]. In a study of the degenerative lesions in the articular cartilage after meniscectomy in dogs[13], it was found that lesions proved to be more intense at the tibial plateau compared to the femoral condyle.

The impact of an absent meniscus becomes more significant when the anterior cruciate ligament is absent[14]. Previous studies in the assessment of long-term survival rates of repaired menisci showed that significant increases in retear rates were encountered in unstable knees (anterior cruciate ligament deficient)[15]. The interplay of anterior cruciate ligament and meniscus in overall knee kinematics and stability is significant. It is no wonder thus that the combined effect of instability from anterior cruciate ligament and meniscus deficiencies has been found to most likely lead to the development of knee arthrosis[16,17]. Also in advanced osteoarthritis, anterior cruciate ligament integrity strongly influences the articular wear patterns[18]. The anterior cruciate ligament deficient wear patterns showed a wear mechanism that was consistent with the posterior femoral subluxation and posterior tibiofemoral contact[18].

The combined deficiency of the anterior cruciate ligament and the meniscus would thus be indicative of a tibiofemoral contact that engaged the articular cartilage that previously was covered by the meniscus. In view of this pathomechanical occurrence, there have been little or no discerning studies performed on the mechanical properties of normal articular cartilage beneath the meniscus. Biomechanical models to study knee joint kinematics and kinetics, especially those requiring the input of consequential and relevant material properties may benefit from the reality of information pertaining to topographical variation of cartilage properties. Therefore in this study mechanical and structural properties of the articular cartilage covered by the meniscus were determined and compared with that *not* covered by the meniscus.

Materials and methods

SPECIMENS

Seven tibia specimens were obtained for this study. The specimens came from a population of fresh-frozen male cadavers with ages ranging from 62 to 70 years. The specimens were obtained from bodies that had been donated to

*Address correspondence and reprint requests to: Ashvin Thambyah, Ph.D., Department of Chemical and Materials Engineering, School of Engineering, University of Auckland, Private Bag 92019, Auckland 119074, New Zealand; E-mail: ashvin.thambyah@auckland.ac.nz

scientific and medical research, under administrative control of the Health Science Authority of Singapore. Careful gross examination was performed to exclude knees that had obvious injury or damage to the articular cartilage.

GROUPS

Mechanical testing using an actuator with a plane-ended impermeable indenter was performed on the articular (hyaline) cartilage of the medial and lateral tibial plateaus, including the areas beneath the meniscus (Fig. 1). Four sites of the articular cartilage on the tibial surface were thus generalised into four respective groups. These four groups were named and described as follows:

- Group I: Lateral tibial plateau that is *not* covered by the meniscus.
- Group II: Medial tibial plateau that is *not* covered by the meniscus.
- Group III: Lateral tibial plateau that is covered by the meniscus (beneath the meniscus).
- Group IV: Medial tibial plateau that is covered by the meniscus.

In Groups I and II, the central section of the cartilage not covered by the meniscus was tested. This was the region of the articular cartilage subjected to direct weight-bearing. The region tested in Groups III and IV was in the posterior section of the tibial plateau beneath the meniscus. This was the region of articular cartilage most likely involved in tibiofemoral contact in the anterior cruciate ligament and meniscus deficient knee.

INDENTATION TEST

Cartilage indentation mechanical tests performed in the present study followed similar testing protocols of previous methods[19–21]. The properties derived in the present study

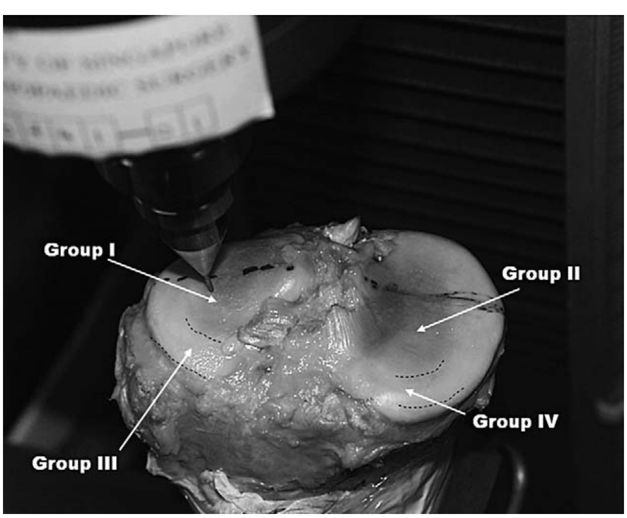

Fig. 1. The dotted line represents the outline of the removed meniscus. The four sites of the articular cartilage for mechanical testing on the tibial surface were divided into four groups. Group I: Lateral tibial plateau that was *not* covered by the meniscus. Group II: Medial tibial plateau that was *not* covered by the meniscus. Group III: Lateral tibial plateau that was covered by the meniscus. Group IV: Medial tibial plateau that was covered by the meniscus.

to represent modulus were that obtained instantaneously and not after a process where the cartilage was subjected to long periods of creep until equilibrium was reached. The rationale for this approach is that during the instantaneous response after load application, the cartilage can be modelled as an incompressible single phase elastic material[20,21]. Mak *et al.* (1987) validated their conclusions on the basis that the absolute values of instant and equilibrium shear moduli differed from each other but they revealed the same variation in topographical stiffness[21]. In the present study, instead of measuring equilibrium modulus, the instantaneous modulus was measured. This removed the need to subject the cartilage to long periods of exposure for equilibrium to be reached. To achieve this, a rapid loading rate was necessary to eliminate (or decrease) the effects of creep.

Tibial plateau specimens were prepared with the meniscus removed (as shown in Fig. 1). The cartilage was loaded in axial compression at a constant load of 0.5 N, with the use of a 1-mm diameter indenter, attached to a 500 N load cell of a materials testing system (INSTRON® model number 5543, Massachusetts, USA). This resulted in a 0.6 MPa applied-stress. The small size of the indenter was intended to minimise the influence of the stiff underlying bone on the registered force[21]. The indenter start position was achieved by adjusting the specimen until the cartilage surface was just in contact and perpendicular to the long axis of the indenter. The specimen was locked in place once this position was reached by careful visual observation. The cartilage was indented with a steep ramp function (rise time < 200 ms). The loading rate with this configuration was equivalent to no less than 300 kPa/s until a load of 0.5 N (0.6 MPa) was reached. The load was then kept constant throughout the test. The constant load was obtained by the load control system of the materials testing machine, with the gain set at 30 dB for optimum feedback control. The actuator maintained a constant 0.5 N load throughout the creep test that lasted for 60 s, following which the cartilage was unloaded. After about 5 min, total recovery of the indented surface was observed and the testing ended. The test was repeated until steady state was reached and repeatable response was obtained. Force, extension and time parameters were recorded throughout the tests.

CARTILAGE THICKNESS MEASUREMENT

The thickness of the cartilage was determined by penetrating the cartilage with a fine needle and at a slow rate (0.1 mm/s)[22]. The thickness was calculated as the distance between surface detection and the rapid increase in force when the needle reached calcified cartilage and subchondral bone.

DERIVATION OF THE MECHANICAL PROPERTIES

Four parameters were derived from the available data of force and displacement from the materials testing system: (1) stiffness (N/mm), (2) creep (mm), (3) instantaneous modulus (MPa) and (4) creep normalised to cartilage thickness. Creep was measured after 60 s with the application of the constant 0.5 N load. The short creep time was used to minimise any effects that could occur from exposure of the fresh cadaver specimen to air. Saline was used to keep the specimen moist throughout the testing.

Instantaneous (Young's) modulus, E, was calculated using the methods described previously[19,23] as follows:

$$E = \frac{P(1 - v^2)}{2a\omega\kappa},$$

where $P =$ load applied (N), $\omega =$ axial displacement of the indenter (mm), $a =$ radius of indenter (mm), $\nu =$ Poisson's ratio, taken as 0.45 (assumed as incompressible)[21,24], $\kappa = f(a/h, \nu)$ a scaling factor (from Hayes *et al.* 1972)[19], and $h =$ cartilage thickness.

Several indentation tests were performed on one site (group) to ensure repeatability. The final value was used. Parameters of mean and median stiffness, creep, moduli, and creep-to-thickness ratios were calculated for the four sites.

HISTOLOGICAL EVALUATION

Histological study was performed on the samples of articular cartilage procured from three tibial plateaus. Using an oscillating saw, the samples were obtained by cutting 5-mm thick slices (sections) of the proximal tibia in the para-coronal plane (Fig. 2). The sections were across the length of the tibial plateau and included regions of cartilage not covered by the meniscus as well as beneath. These sections were then halved into medial and lateral halves. A total of 12 such halved samples were selected for histological preparation, six for the medial side and six for the lateral side.

Each specimen was fixed in 10% buffered formalin for a week, decalcified in 30% formic acid for about 3 weeks, dehydrated and cleared in alcohol and toluene and finally embedded in paraffin blocks. Ten microns of decalcified sections were then cut using a rotary microtome for staining with Haematoxylin and Eosin and Safranin O stains. The histological structure of the articular cartilage was studied under the microscope at a magnification of ×50. All the images were digitised for detailed histological analysis. The histological status of the articular cartilage was evaluated[25] and graded according to Mankin's scoring system[26]. Digital imaging software was also used to study the thickness of articular cartilage (mm), density of subchondral bone and thickness of the calcified layer (mm). The apparent density of subchondral bone was estimated from digital image analysis that magnified into the area of interest. This area of interest was uniform for all slides investigated according to the zones described (Fig. 2). From the digital imaging software, a frequency distribution histogram of the image facilitated the selection of the greyscale level representing the subchondral bone on the image. The number of pixels associated with the particular greyscale level was recorded as a percentage of the entire region's pixel number. This was done for all the three regions investigated.

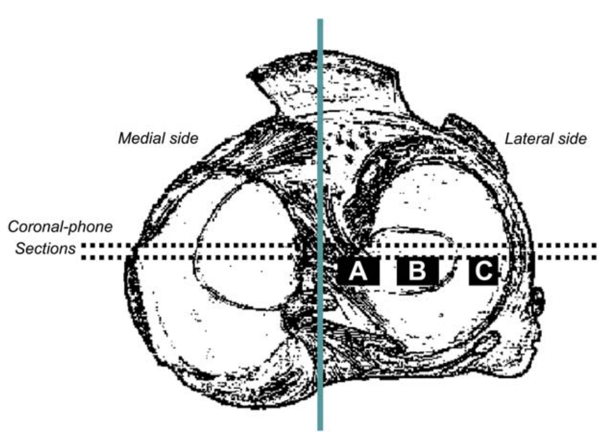

Fig. 2. Coronal plane sections of 5 mm thick were obtained using an oscillating saw. These sections were halved into medial and lateral. For the histological study, from each half, 10 micron-thick decalcified sections were obtained for staining with Haematoxylin and Eosin and Safranin O stains. The areas A, B and C show three distinct zones. Zone B is the cartilage that is not covered by the meniscus. Zone C is that covered by the meniscus. Zone A, close to the tibial eminence, represented cartilage *not* covered by the meniscus but, compared to zone B, was assumed to be a region subjected to less loading during weight-bearing.

Table I
Results of mechanical testing

($N = 7$)		Stiffness (N/mm)	Creep (mm)	Modulus (MPa)	Creep/ thickness (%)
Group I	Mean	4.87	0.17	2.13	4.34
	SD	3.75	0.05	0.74	1.39
Group II	Mean	10.99	0.11	3.51	2.79
	SD	4.67	0.05	1.42	1.20
Group III	Mean	20.38	0.08	3.77	2.07
	SD	5.32	0.02	1.25	0.63
Group IV	Mean	20.08	0.07	5.13	1.82
	SD	5.76	0.02	1.91	0.60

STATISTICAL ANALYSIS

Data from mechanical testing were from four groups (Fig. 1), while the data from the histological evaluation represented three sections (refer to Fig. 2) of the medial and lateral sides.

A comparison of the data from mechanical testing between the groups with respect to the variation was performed using non-parametric analysis with SPSS software (SPSS Inc., Chicago, USA). A Kruskal–Wallis test was used to test the null hypothesis that the medians were similar for a given parameter between groups. The degree of freedom of the Kruskal–Wallis test ($N = 7$) was 3 and the critical chi-square values were 7.81 (alpha at 95%) and 11.34 (alpha at 99%). Differences between groups were delineated using a Wilcoxon signed-ranks test to investigate comparisons for: Group I vs Group II, Group III vs Group IV, Group I vs Group III, and Group II vs Group IV. The null hypothesis was that there would be no significant difference between these groups. Significant difference was

Table II
Comparison of articular cartilage mechanical properties between groups (refer to Fig. 1 for group descriptions)

Parameters studied	Comparing groups			
	I vs II	I vs III	II vs IV	III vs IV
Stiffness	I < II*	I < III*	II < IV*	0.735
Creep	I > II*	I > III*	*No difference*	*No difference*†,*
Modulus	I < II*	I < III*	*No difference*†	III < IV*
Creep/thickness	I > II*	I > III*	*No difference*	*No difference*

*Significant ($P < 0.05$).

†Marginal significance ($P < 0.07$).

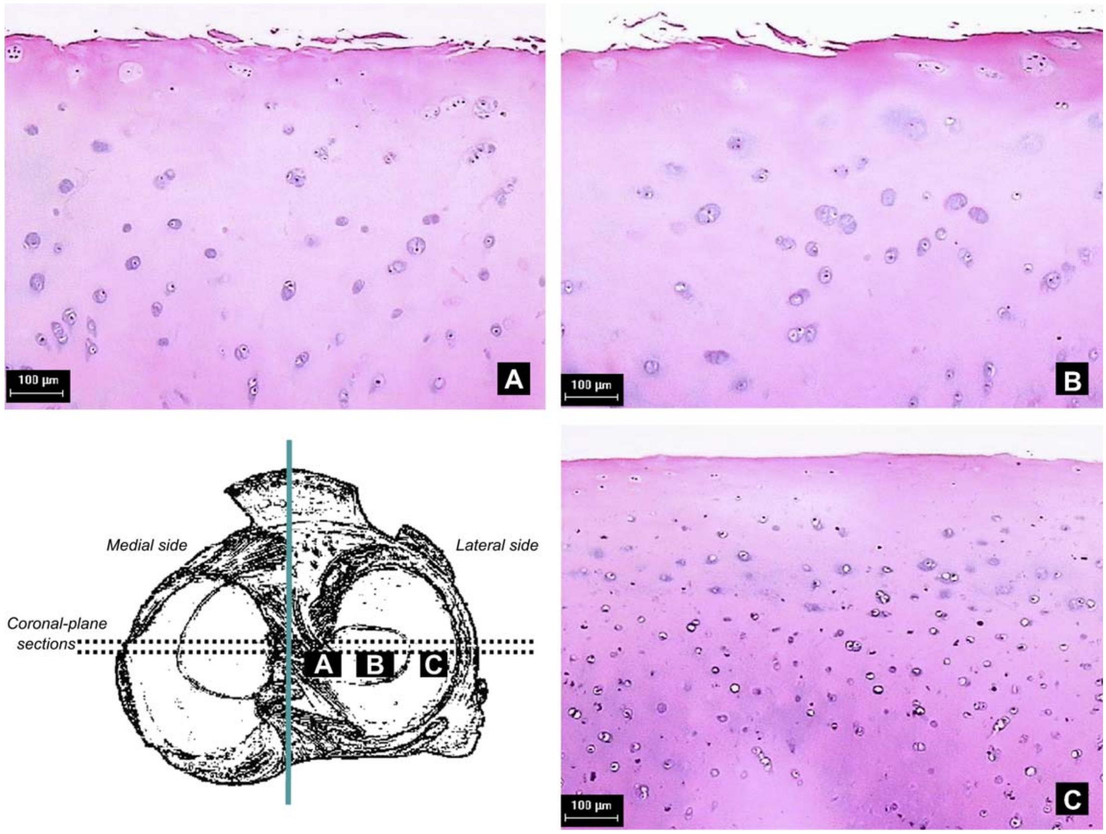

Fig. 3. (A and B) Showing at a magnification of ×50 the histological sections of the zones of articular cartilage of the lateral tibial plateau of the same cadaver stained with Haematoxylin and Eosin. Fig. 3(A) showing cartilage in zone A, 3B and 3C in zones B and C, respectively. Mankin score for structure was rated as 1 for A, 1 for B and 0 for C. All the cells were rated 0 (normal) in zones A, B and C.

taken to occur when $P < 0.05$. Correlation coefficient (r) was also calculated to study the relationship between creep and stiffness.

To examine variation in the data collected from the histological sections, a one way ANOVA design was used followed by *post-hoc* Tukey to define significant differences between specific sections. Significance was taken at $P < 0.05$.

Results

Summaries of the average values and standard deviations (SDs) of mechanical properties obtained for the groups studied are shown in Table I. Non-parametric statistical analysis of the data using Kruskal–Wallis test on the medians indicated that the mechanical properties of stiffness, creep, and modulus were all significantly different among the four groups or sites tested with chi-square values of $\chi^2 > 12$, ($P < 0.01$). Wilcoxon signed-ranks tests revealed that, contrary to the null hypothesis, there was a significant difference between the groups in several of the comparisons (see Table II).

STIFFNESS (N/MM)

There was a significantly[a] larger stiffness recorded in Group II vs Group I, the medial and lateral plateaus of the regions *not* covered by the meniscus. This increase, in comparing the means, was in the order of about 120%. Group IV, the region on the medial side covered by the meniscus, was significantly larger by about 80% of Group II. Group III, the region on the lateral side covered by the meniscus, had significantly larger stiffness than Group I, by about 300%.

[a]Significant here refers to $P < 0.05$.

CREEP AND CREEP-THICKNESS RATIO

Axial creep measured after 60 s of constant axial load was different between the sites tested. The most creep was observed in Group I, and the least creep occurring in Group IV. Creep in Group II was significantly less than Group I by about 35%. Group III creep was also significantly less than Group I, and by about 53%.

Articular cartilage thickness was found to be significantly thinner in Groups III and IV, the regions covered by the meniscus. The cartilage in Groups I and II was about 30–40% thicker than the articular cartilage in Group III and up to 80% thicker in Group IV, respectively. A summary of the thickness measured is as follows: Group I was 3.9 mm (SD, 0.9 mm); Group II 3.2 mm (SD, 0.04 mm); Group III 1.7 mm (SD, 0.1 mm); and Group IV 2.1 mm (SD, 0.1 mm).

INSTANTANEOUS (YOUNG'S) MODULUS

In the regions *not* covered by the meniscus, the modulus was significantly larger in Group II, the medial side, compared to Group I by about 64%. Group III modulus was also significantly larger than Group I and by about 77%. Finally Group IV modulus was significantly larger than Group III by 36%. The difference between Group II and Group IV was *marginally* significant ($P < 0.07$).

CORRELATION BETWEEN STIFFNESS AND CREEP

When correlating stiffness (N/mm) with creep (mm) in the regions *not* covered by the meniscus, R was -0.91 and -0.77 for Groups I and II, respectively; while for Groups III and IV, the regions covered by the meniscus, it was -0.41 and -0.70, respectively.

HISTOLOGY

Histological analysis of the articular cartilage for all specimens stained with Haematoxylin and Eosin as well as Safranin O staining according to Mankin's scoring system[26] gave total scores ranging from 0 to 2. Our findings showed that in all specimens zones A and B gave scores of 1 (surface irregularities only) compared to a score of 0 (normal) for zone C (Fig. 3). With regard to cells all sections gave a score of 0 (normal) (Fig. 3). Safranin O staining revealed scores of 1 (slight reduction) for zones A and B, and 0 (normal) for zone C (Fig. 4).Tidemark integrity was rated as 0 (intact) for all sections in zones A, B, and C (Fig. 5).

Discussion

The stiffness (N/mm) values obtained in this study for the articular cartilage in the regions not covered by the meniscus may be compared with previous reports[20]. In the previous study, the authors measured *in-vivo*, the force required to indent 300 microns into the articular cartilage. They obtained force readings that averaged 2.4 N for the medial tibial plateau and 3.1 N for the lateral. These force values when normalised to the 300 micron fixed displacement, represent stiffness values of 8 N/mm and 10 N/mm for the medial and lateral plateaus, respectively. These stiffness values derived from the previous study[20] may be compared to that from the present study where Group II (the medial side, not covered by the meniscus) and Group I (lateral) showed stiffnesses of 11 N/mm and 5 N/mm, respectively. Differences could be due to several reasons. The most obvious reason would be that while in the previous study[20] the average age of the patients was 26 years, the specimens in the present study came from an older age group of donors where age-related changes may have influenced the results obtained. In the present study (according to Mankin's grading system) the articular cartilage covered by the meniscus was normal (0), compared to the articular cartilage not covered by the meniscus where the score ranged from 1 to 2. Also the previous study[20] used a hand-held indenter in arthroscopy and measured *in-vivo* loads via displacement control;

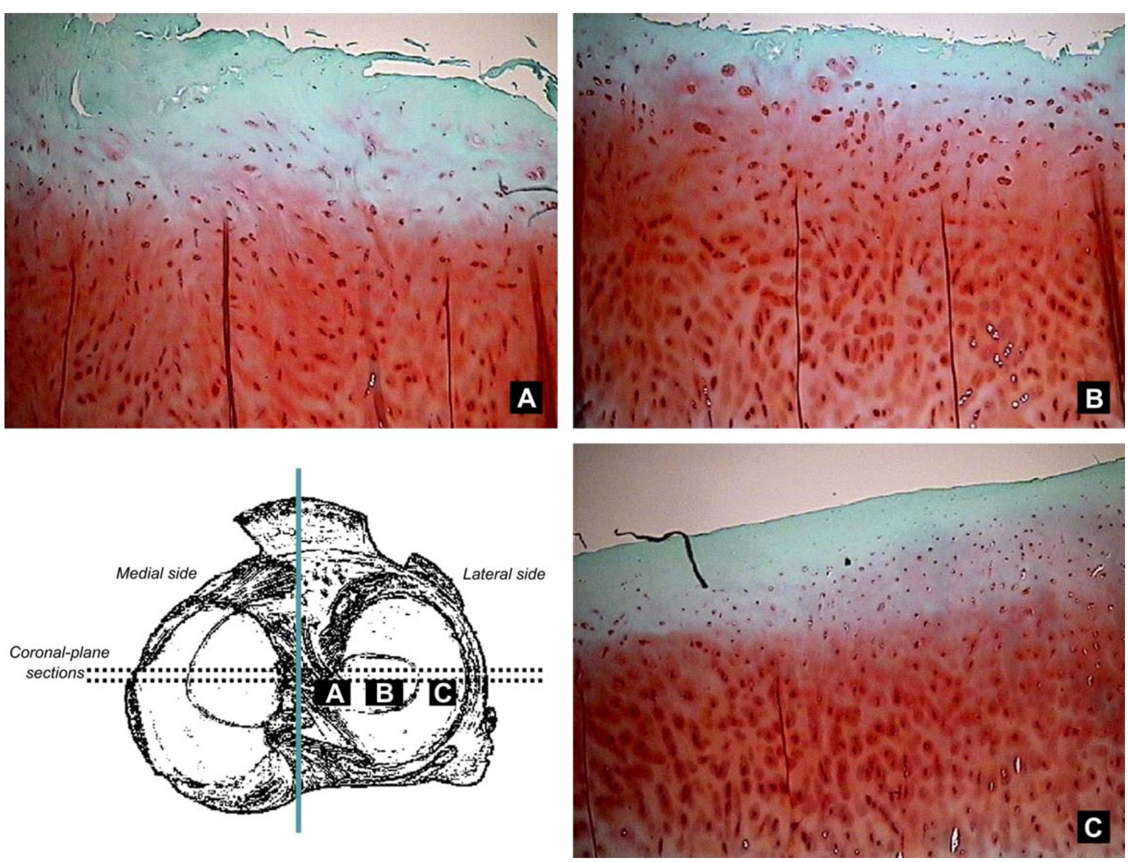

Fig. 4. (A–C). Showing at a magnification of ×50 the histological sections of the zones of articular cartilage of the lateral tibial plateau of the same cadaver stained with Safranin O. Fig. 4(A) showing cartilage in zone A, 4B and 4C in zones B and C, respectively. The intensity of staining was graded as 1 (slight reduction) in regions A and B, and 0 (normal) in region C.

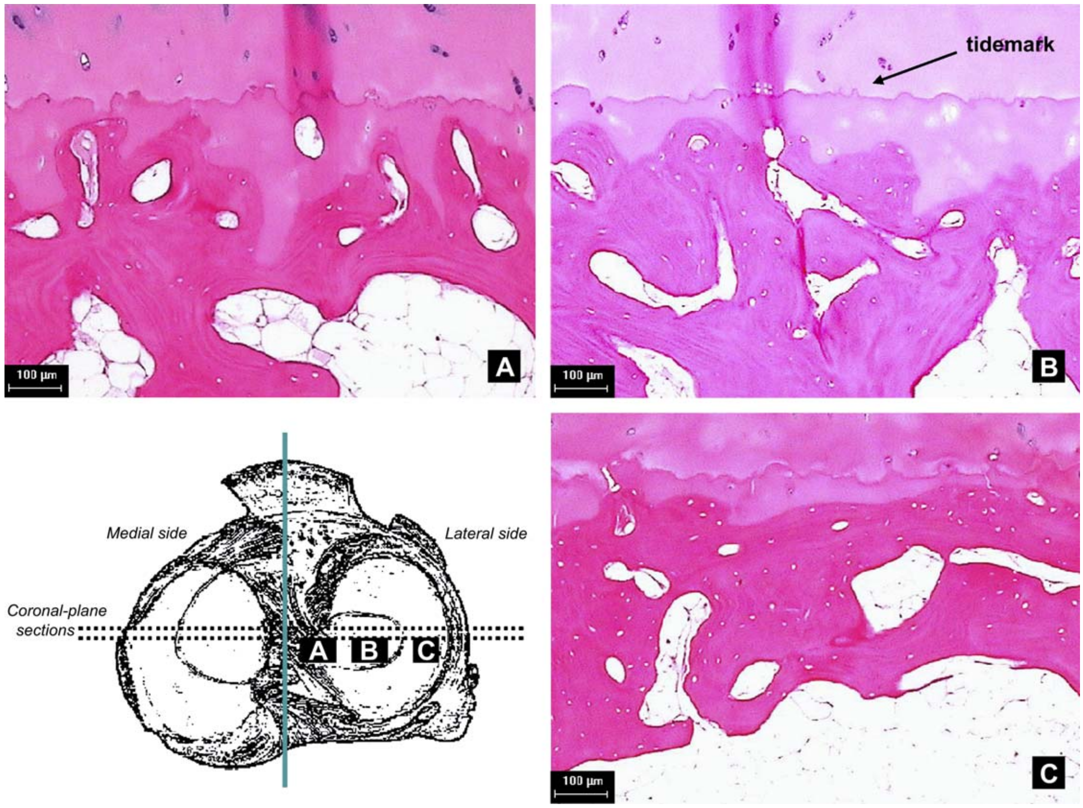

Fig. 5. (A–C). Showing at a magnification of x50 the histological sections of the zones of subchondral bone region of the lateral tibial plateau of the same cadaver stained with Haematoxylin and Eosin. Fig. 5(A) showing cartilage in zone A, 5B and 5C in zones B and C, respectively. Intact tidemark with a Mankin score for tidemark integrity of 0 was found in all regions.

whereas in the present study the *in-vitro* experiment was performed via load control.

The thickness of the articular cartilage not covered by the meniscus measured in the present study was similar to that measured in previous studies of elderly subjects[27]. Comparing with thickness measurements averaging about 1.5–1.8 mm from previous studies using quantitative Magnetic Resonance Imaging (MRI)[28] the thickness values of some 3–4 mm obtained in the present study on the cadavers of the all-male donors were relatively larger. However, compared to earlier MRI studies[29] who obtained measurements in the region of 2–3 mm, with maximums reaching 5 mm, the present study's thickness measurements are comparably similar. In any case one

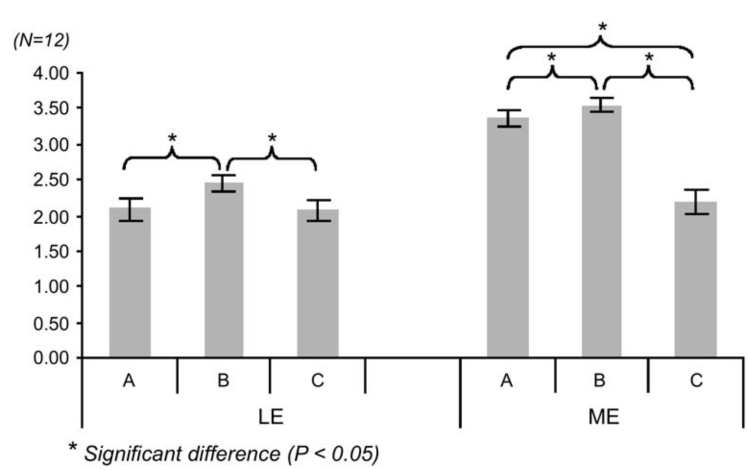

Fig. 6. Thickness of the articular cartilage layer (mm) determined from histological sections. Lateral side (LE) and medial side (ME) differences were obvious. Also compared to the region of articular cartilage *not* covered by the meniscus (regions A and B) the region covered by the meniscus (C) was significantly thinner.

would question the accuracy of using the needle method in the present study to determine cartilage thickness, as the method depended on the sensitivity of the measuring load cell and the point at which the needle encountered a sudden rise in resistance to its progression into the cartilage. Essentially the expectation was for the needle to encounter this sudden increase in resistance as it hit the calcified layer, which is a rather difficult region to define with respect to the underlying bone. In any case, the finding in the present study that showed articular cartilage covered by the meniscus to be thinner than the cartilage that was not covered, supported similar findings from previous studies that reported variations in cartilage thickness in the knee[30,31]. These variations across the tibial plateau were most likely due to the load experience that indicated a tendency for thicker cartilage to be found in regions that experienced more dynamic loading activity[32].

The modulus (MPa) and creep (relative to cartilage thickness) were parameters that had been derived through a normalisation procedure where the cross sectional area of the indenter was taken into account as well as the thickness of the cartilage tested. The sites beneath the meniscus seemed to be more sensitive to the effects of this normalisation as shown by the weaker correlations when comparing simply the stiffness (N/mm) and creep (mm) values. The relationship showed that the articular cartilage with the tendency to creep more had less stiffness. The creep modulus in the present study assumed a scaling factor corresponding to a Poisson ratio of 0.45 which was close to that of an incompressible material. Studies have reported Poisson's ratio of articular cartilage to be as low as 0.2[22], but the scaling factors given previously[19] did not include those for studying materials with Poisson's ratio less than 0.3. A more recent study[33] looked at the scaling factors that would be relevant to studying materials with small Poisson's ratios and found that for the dimensionless ratio of indenter radius and tissue depth, the errors in estimating the scaling factor increased with decreasing indenter size. This made it difficult to compare measurements obtained in the various studies including the present. In the present study, using a Poisson ratio of 0.45 and an indenter radius to thickness (aspect) ratio of about 0.2 (depending on the thickness of the cartilage), a reasonable estimate of the scaling factor was derived. However, more investigation has to be done with respect to the effects of Poisson's ratio, indenter size and cartilage thickness in order to obtain a more relevant estimation of scaling factors that needs to be used in these calculations. In any case, the results of the present study showed articular cartilage mechanical properties beneath the meniscus to be different from that in the region not covered by the meniscus. This corroborated the finding from a previous study[34] where it was found that the instantaneous compressive modulus of human articular cartilage was significantly stiffer in the regions covered by the meniscus compared to the regions that were not.

The observations on morphometry from the histological sections in the present study shed some light as to what these differences in mechanical properties may mean. From our results, it seems that the density of subchondral bone was largely influenced by the loading history. Our results (Fig. 7) showed that region B, which was the area not covered by the meniscus, was most dense in subchondral bone compared to regions A and C. Region A was the section close to the tibial eminence and region C represented the area covered by the meniscus (refer to Fig. 2). Region A was taken as a region that was *not* covered by the meniscus and assumed to have a less loading history compared with region B, which is also not covered by the meniscus. In the normal knee joint the tibiofemoral contact was likely to be confined largely to region B and hence it could be expected that the subchondral bone here would be denser. Interesting also to note was that the articular cartilage thickness was affected by both location (region B having thicker cartilage than region C) and by loading history as observed in differences between regions A and B (see Fig. 6), albeit to a lesser effect than that observed for subchondral bone density. However, the least effect of loading history seemed to be on the calcified layer thickness which showed no significant differences between regions A and B (Fig. 8). The effect of loading history on the subsequent development of articular cartilage, the calcified layer and subchondral bone morphology seemed to be different.

The morphological differences between the articular cartilage of the regions *not* covered by the meniscus (region B) and that covered (region C) were shown to be significant. Figures 6–8 showed that the regions B vs C were consistently different in that B was larger than C for all the morphological parameters measured. The thickness of the articular cartilage from the histological observation showed as much

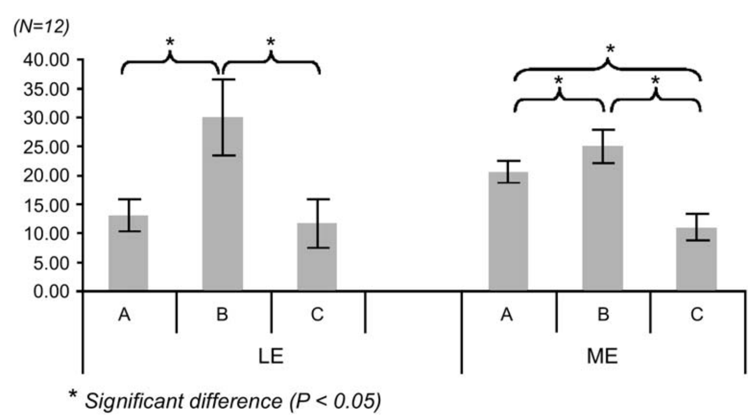

Fig. 7. Showing the density of subchondral bone, represented as pixel number relative to the rest of the image (%), of the lateral side (LE) and medial side (ME). For both sides, the density was shown to be largest in the region that was not covered by the meniscus and subjected to the largest loading history, which was region B.

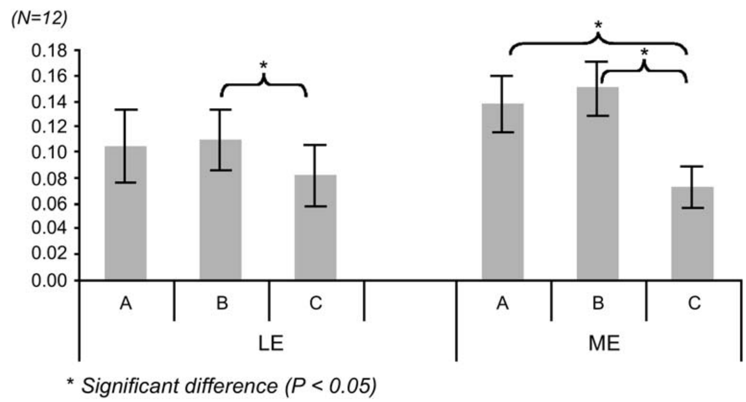

Fig. 8. Showing the average thickness of the calcified layer (mm) of the lateral side (LE) and medial side (ME). The medial side cartilage displayed a larger thickness with significantly larger thickness in the regions not covered by the meniscus (A and B) compared to the regions beneath (C).

as a 50% drop in thickness moving from region B to C. The mechanical testing had revealed that both the stiffness (N/mm) and modulus (MPa) increased from the region uncovered by the meniscus to the region beneath the meniscus. Thus in summary compared to the articular cartilage not covered by the meniscus, the articular cartilage of the region beneath the meniscus was stiffer, yet thinner, and had less dense subchondral bone. This would suggest that the capacity for load bearing in the articular cartilage of the region covered by the meniscus was likely to be different from that of the region not covered by the meniscus given the differences in the morphometry and mechanical properties. A stiffer articular cartilage principally transfers loads across more efficiently to the next material in-line beneath it, and that would be the subchondral bone. The load dissipation or damping would thus be reduced in the composite and the underlying subchondral bone would be the most likely to receive more loads when the cartilage beneath the meniscus is directly loaded. In the present study the subchondral bone content was found to be significantly reduced in the areas covered by the meniscus which also showed significantly reduced thickness in the articular cartilage. The combination of these reductions presented very little evidence that the cartilage regions covered by the meniscus would be as adequately prepared to weight-bear in the absence of a meniscus, as the regions *not* covered by the meniscus.

Besides the obvious concern about the load bearing differences between the articular cartilage from the two regions in relation to altered joint mechanics from an anterior cruciate ligament and meniscus deficient knee, there were other concerns. One worth mentioning for discussion involved bone that has suffered some form of minor injury, such as a bone bruise. Bone bruising, an occult trabecular microfracture of bone typically located close to a bone surface and caused by compression or impaction forces has been found to be prevalent in anterior cruciate ligament deficient patients[35,36] and other instabilities[37,38]. This would pose an additional conundrum for the appropriate modelling of the pathomechanics of the anterior cruciate ligament deficient knee without the meniscus, when trying to include the remodelling features of the bruised subchondral bone.

The knowledge of the topographical variations of articular cartilage material properties is important in terms of the way load is transferred to the subchondral bone because of either altered kinematics or changes in material properties, and even to bone that has suffered some microfracture. It is hoped that the interpretation of the data made in the present study would be useful to colleagues for future work in this area, especially in the design rationale for biomechanical models. It is foreseeable that such models would be useful for the analysis of the influence of knee instabilities on joint trauma and the consequential development of the joint degenerative process as a result of such trauma.

Conclusion

This study showed that there were significant differences in the articular cartilage over the tibial plateau. The articular cartilage covered by the meniscus was found to undergo less creep, was thinner, and had a higher modulus than that not covered by the meniscus. Also the effects of loading history were more apparent in subchondral bone formation than in articular cartilage thickness, while none was seen in the calcified layer morphology. Our findings revealed a significant difference between the mechanical properties and associated structures of articular cartilage in the region covered by the meniscus compared with the articular cartilage not covered by the meniscus.

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